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HYD 373

SOME HYDRAULIC ENGINEERING ASPECTS OF
DENSITY CURRENTS

Hydraulic Laboratory Report No. Hyd-373

ENGINEERING LABORATORIES BRANCH



OFFICE OF THE ASSISTANT COMMISSIONER AND CHIEF ENGINEER
DENVER, COLORADO

August 31, 1954

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Hydraulic Laboratory
Compiled by: E. W. Lane
Reviewed by: E. J. Carlson

Subject: Some hydraulic engineering aspects of density currents

INTRODUCTION

Density currents have been defined by Bell (4)^{1/} as "a gravity flow of a fluid through, under, or over a fluid of approximately equal density." Such currents cause a number of effects which are of importance to the hydraulic engineer, and he should therefore be aware of them. It is the purpose of this report to bring together from widely scattered sources some of the most important information on this subject.

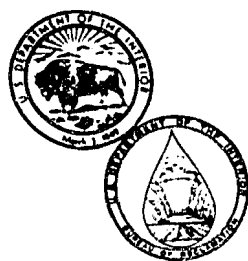
Density currents are very common, as many large scale movements of air masses in the atmosphere are in this class. Cloud or fog movements and dust storms are other examples. These currents range in size from actions covering a good fraction of the earth's surface to minute movements of mud in a puddle.

Causes of Density Currents

The density currents which are of interest to the hydraulic engineer and are treated in this paper are those which occur in rivers, reservoirs, lakes or the oceans, and involve flows of water. They may be grouped into three classes, according to the causes of their motion. One class covers currents with movement due to the suspension of sediment in the flowing water, and usually involves the deposition of sediment in reservoirs. This class has been called turbidity currents. A second class covers those density currents caused by dissolved material in the water, and is important from the standpoint of the suitability of water for irrigation or domestic use. The third class is movements due to difference in densities set up by differences in temperature in the water, and is of interest in connection with the quality of water from reservoirs used for public water supply.

Since density currents are due to differences in density of the fluids involved, they may be due to any single cause which sets up differences of density, or to any combination of causes. For example, in

^{1/} Numbers refer to articles in the bibliography at the end of this report.



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Since density currents are due to differences in density of the fluids involved, they may be due to any single cause which sets up differences of density, or to any combination of causes. For example, in

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Lake Mead in the Lower Colorado River, in southwestern United States, sediment content, salt content, and temperature are all three of importance and may act in combination.

Since density currents are flows of a fluid, through, under, or over another fluid, they may also be classified according to whether the flow of the one fluid is through, under, or over the other. The density currents which flow through another fluid are called interflows, those which flow under another fluid are underflows and those which flow over the other fluids are overflows. It is possible to have a combination of these types, for example, a flow may start as an underflow and then become an interflow.

Underflow Turbidity Currents

One of the common types of density current is the underflowing turbidity current, Figure 1, which moves down the bottom of the reservoir, due to the greater density of the turbid water resulting from the inclusion of suspended sediment. For example, currents of muddy water have been observed to flow down the bottom of Lake Mead for over a hundred miles, under a quiet body of clear water the surface of which was practically level. The force which causes motion is the greater density of the muddy water, and the magnitude of the force depends on the difference of density of the muddy and clear water, the depth of the flow, and the longitudinal slope of the reservoir bottom. Because of its greater density, the turbidity current usually follows the lowest path down the reservoir. In some cases it deposits part of its sediment as it flows, and in other cases it appears to deposit little if any material. Initially the flow closely follows the original stream channel down the bottom of the reservoir, but the inertia effects at bends are more pronounced than in ordinary flows, and such currents have been known to rise up and go across a bend, rather than following the lower bottom around it. This is possible because the effective weight of the turbidity current is much less than in ordinary flows, as the effective weight is only the difference in weight of the clear and turbid water, and may be as little as $1/1000$ of the actual weight.

When such a current reaches a dam in which there are openings at river bed level, the turbidity current will flow out in many cases without mixing with the clear water. If the discharge of the turbidity current is greater than the discharge capacity of the sluices, part of the flow may be temporarily stored in the bottom of the reservoir, like a flood flow in a retarding basin. If there are no openings, the turbidity current tends to form a lake of muddy water in the bottom of the reservoir under the clear water.

The turbid water flowing into a reservoir may plunge directly under the clear water in the lake as shown in Figure 1. In this case it sets up an upstream current on the surface of the clear water, as indicated by the arrows. Where this upstream flowing current of clear water meets the downstream flowing muddy water, drift brought down the stream may collect on the surface in large quantities.

Because of the drift on the surface and the sharp line of separation of the muddy and the clear water, the formation of a turbidity current as just described is readily apparent. There is reason to believe, however, that in many reservoirs the inflowing water does not dive under the clear water, but pushes it downstream and forms a considerable body of muddy water, in which the sediment is slowly settling to the bottom as shown in Figure 2. When this sediment reaches the bottom, some of it collects in the form of a dense fluid, which flows down the banks to the main channel and then flows down the main channel in an underflowing turbidity current, as in the previous case. This means of formation of a density current is not so easily detected as the one previously described and has not been directly observed but its existence is inferred from the deep deposits of fine material in the stream bed near the upper ends of some large reservoirs. These deposits are much deeper compared with the deposits outside the channel, than would occur if there were no movement of the settled sediment after it reached the reservoir bottom. In the upper end of Lake Mead, deposit, except in the stream channel, is usually nonexistent, although muddy water has frequently covered much of the upper end of the reservoir, and no doubt much of this sediment has settled to the bottom. Underflow type of turbidity currents sometimes occur as the result of suspension of sediment caused by wave action on the shores of reservoirs. In this case the flow is from the banks at the edge of the reservoir to the bottom of the reservoir.

The velocity of flow in an underflow type of turbidity current depends on the density of the turbid water, the depth of the flow, and the steepness of the channel. The force per unit volume causing the flow increases with an increase in the difference in density between the two fluids. It increases with an increase in the bottom slope and with an increase in the thickness of the heavier liquid. Ordinarily the velocity of flow is less than 1 foot per second, but some authorities believe that much higher velocities are sometimes attained. Density currents have been used to explain the formation of submarine canyons in the ocean, and the presence of sand and gravel on the sea bottom at large distances from the land and at great depths. Under such conditions the slopes are steeper than usually found in reservoirs, and the velocities are probably higher.

Interflow and Overflow Turbidity Currents

When the clear water in the different levels of reservoirs has considerably different densities, interflows may be formed. Frequently the water near the surface of a reservoir is much warmer and therefore lighter than the water near the bottom. If turbid water with a density between the light surface water and heavier bottom water enters such a reservoir it is likely to form an interflow. The turbid water flows along the reservoir bottom as an underflow, until it reaches a layer of the colder bottom water which has a greater density. The turbid water then flows along the top of this layer, forming an interflow between the two layers of clear water.

When the inflowing turbid water has a density less than the water in the reservoir, it will flow out on top of the denser water, causing an overflow type of turbidity current. A common case of this type occurs when a river of turbid water enters the salt water of the ocean, and it flows out into the ocean on top of the heavier salt water. The Mississippi River flows for many miles out into the Gulf of Mexico as an overflow type of density current. Although it contains sediment, it is less dense than the salty ocean water.

In any one reservoir, the conditions may change so that more than one type of turbidity current is formed. In Lake Mead above Hoover Dam, underflow, interflow, and overflow types have all been observed.

Data on Turbidity Currents in Reservoirs

The most complete data on turbidity currents in reservoirs deal with those which have occurred in Lake Mead, above Hoover Dam on the Lower Colorado River (1, 2, 3, 9, 12C, 36, 41, and Appendix I). Considerable data are also available on the Elephant Butte Reservoir (3, 15, 18, and Appendix I) on the Rio Grande in New Mexico, on the Conchas Reservoir (11) on the South Canadian River in New Mexico, and on Lake Texoma on the Red River in Texas and Oklahoma. Some observations have been made on Lake Issaqueena (14) in South Carolina and Lake Lee (16) in North Carolina and Morris Reservoir in California. Density currents have also been observed in Lake Kemp in Texas, Santa Anita and Morena Reservoirs in California, Echo Reservoir in Utah, Norris Reservoir and the lake above Wilson Dam in Tennessee, Lock Raven Reservoir in Maryland, Zuni Reservoir in New Mexico, Lake Murray in South Carolina, Ashokan Reservoir in New York, and Lake Arthur (5) in South Africa.

Data on some density currents observed in a few of the reservoirs mentioned are included as Appendix I to this report. A rather extensive bibliography is included as Appendix II.

Possibility of Decreasing Deposits in Reservoirs by Venting Turbidity Currents

The possibility of decreasing the rate of filling of reservoirs with sediment by venting the turbidity currents of the underflow type has been widely discussed (2, 3, 5, 6, 7, 14, 18) and examples of such currents being discharged from reservoirs are numerous. Arguments both for and against this process as a means of decreasing reservoir deposits have been made.

The reduction of deposits by this method has been used in the Lake Arthur Reservoir in South Africa for flows of flocculated clay with concentrations between a lower limit of 1-1/2 percent to 5 percent and an upper limit of 25 percent. No data from Lake Arthur Reservoir are available on the amount of sediment removed by this process. In order to save water, the inflowing turbidity current is retained until its sediment

has settled down to near the maximum concentration at which it will flow out through the gates, and this concentrated slurry is then drawn out.

The experience with reservoirs in the United States has not been encouraging to the venting of density currents as a means of substantially reducing sediment deposits in reservoirs. In the early years of use of the Elephant Butte Reservoir on the Rio Grande, these currents brought sediment down to the dam and it was discharged through the outlet in the bottom of the dam. Some irrigators downstream often declined to use the water, as it had no fertilizing value, and if used to irrigate newly planted land, killed the young sprouts. Irrigators whose land was too sandy, however, eagerly sought the water, as it improved the texture of their soil. Even in the early years of Elephant Butte Reservoir, where the conditions are especially favorable to the formation of such currents, the sediment discharged in this way was less than 5 percent of that entering the reservoir. In recent years, no turbidity currents have reached Elephant Butte Dam.

The frequency of turbidity currents in Lake Mead on the Colorado River has been lower in recent years than soon after the reservoir was built. The reason for the decreased frequency of flows in Lake Mead and Elephant Butte Reservoirs is probably that the deposits on the lake bottoms formed by the turbidity currents are level across the reservoirs, and the density flows pass over these bottoms in a thin sheet. As the deposits fill the valley, the width of these deposits increases and the depth of flow of the currents becomes correspondingly smaller. As the depth of a turbidity current decreases its velocity of flow also decreases, and more of the sediment is deposited on the bottom, and less therefore reaches the dam. At one point in Lake Mead the width of the level bottom has become more than 6,000 feet. Measurements in recent years have shown lower velocities than the velocities in the earlier flows. It seems not improbable that in the future these density currents may cease to reach the dam in both the Elephant Butte Reservoir and Lake Mead.

In the Texoma Reservoir on the Red River, the sediment brought down to the dam by turbidity currents is probably less than 10 percent of the total sediment load. Records of 15 to 30 percent of inflowing sediment reaching the dam was obtained from the Conchas Reservoir on the Canadian River, where the conditions are favorable for turbidity currents. The slopes are steep (8 to 12 feet per mile), sediment concentrations of the inflowing river are high (up to 5.5 percent), and the reservoir is narrow. These values on the Conchas were for the first 11 years of operation, and will likely decrease as the reservoir fills with sediment.

From the foregoing discussion it may be concluded that in most reservoirs the sediment that can be removed by venting density currents will not be a large part of the total sediment inflow. If outlets are placed near the bottom of the reservoir to discharge water for other purposes, they may also be useful to discharge the turbidity currents that occur. Where water is valuable, the practicability of the method described, as used in South Africa should be studied.

Density Currents Due to Dissolved Solids

Density currents are frequently caused by dissolved solids in the water. A very striking case of this kind is observed at the mouth of the Mississippi River, where the muddy water of the river flows for many miles out into the clear water of the Gulf of Mexico, with a sharp line of demarcation between the muddy and the clear water. Here the muddy Mississippi water flows on top of the clear Gulf water, the Mississippi water in spite of its load of sediment, being less dense than the salt water of the Gulf.

An interesting phenomenon occurs in the Mississippi near the mouth at times of very low flow. Here the river water flows downstream near the surface and salt water flows upstream near the bottom.

The Mississippi River reaches the Gulf of Mexico through four principal distributaries, branching off from the main river like toes on the foot of a bird. At the end of each of these channels a bar is formed by a deposit of sediment brought down by the river, over which the depth of water is much less than in the river channel. The depth in the distributaries is somewhat more than that over the bar, and less than the depth in the main river.

At all discharges of the river the greater density of the water in the Gulf tends to produce an underflow of salt water upstream in the Mississippi, but only in times of low flow does it succeed in producing an upstream current. At such times there is an upstream flow of salty water along the river bottom, above which there may be a downstream current of salty water being dragged along by the flow of the river water. For certain flows this condition extends from the Gulf only part way up the distributaries, and no salt water reaches the main river channel. Under other conditions it is possible that the salt water does not mix with the fresh water, but occupies a wedge shaped space below the fresh water, with the thin edge of the wedge upstream. At high flows the drag of the water flowing downstream is sufficient to prevent any density current from flowing upstream and the flow of salt water is thus prevented from entering the distributaries.

At very low discharges the amount of salt water carried downstream is less than the density current flowing upstream, and part of the density current enters the deep channel of the main river. Here the channel is much deeper and the velocity smaller than in the distributaries. The salty water collects in the bottom of this deeper section of the river, and in times of protracted low flow it fills up the low portion and extends upstream many miles, causing bad pollution of the water supply of New Orleans, which takes its water supply from the river about 120 miles above its mouth. When high enough flows occur, the salty water is flushed out into the Gulf again. The salt water, while collected in the deep part of the river, causes much of the sediment brought down by the river to coagulate into a thick slurry, which remains in the deep part of the river until flushed out by the higher flows. While passing out through the distributaries, this slurry has been known to be thick enough to stop the passage of a large steamship.

The upstream flowing "salt water wedges" as they are called occur near the mouths of other rivers entering the sea, and cause trouble where the fresh water of the river is used for domestic or irrigation water supply.

Another case of trouble from density currents occurs where a navigation lock is placed between a fresh water stream or lake and the ocean. Here the salty water flows into the lock when the downstream gates are open, and then upstream through the upper gates when they are opened. If it is desired to have a fresh water condition in the channel above the lock, the salt water entering through the lock may prove to be very undesirable. This condition has occurred at Lake Washington at Seattle, Washington.

Daly (44) describes an interesting situation at the Strait of Gibraltar where the top 200 meters of the opening is occupied by a current flowing into the Mediterranean Sea which may reach a velocity of 4-5 km per hour, and in the bottom 200 meters the current is at about the same velocity toward the Atlantic. These currents are caused by differences of density of the Atlantic and Mediterranean waters that is only 2/1000 of either.

Density Currents Due to Temperature Differences

An interesting case of a density current due to temperature differences, which occurred on a tributary of the Tennessee River (21, 22, 40) due to the dams of the TVA system, may be described as follows:

The town of Harriman, Tennessee, is located on the Emory River at a distance of 14 miles above its junction with the Clinch River. Its waterworks intake is located on the Emory 1-1/2 miles upstream from the place where a paper mill discharges its waste into that stream. It is also upstream from the point where the sewers of the town enter the river. The Watts Bar Dam was constructed on the Tennessee River below the mouth of the Emory River, and backs water upstream above the Harriman intake. In the summer, the Emory River inflow is small, and its water is warm, but the water coming down the Clinch River from the reservoirs upstream is cold. This cold water sometimes flows upstream along the bottom of the Emory River as a density current and carries sewage and paper mill waste upstream to the waterworks intake, thus polluting the water supply. Under certain conditions three levels of flowing water were observed. Water flowed upstream at mid-depth and downstream at both the bottom and top.

Density currents due to temperature differences in lakes have been known for many years. In many lakes in the fall of the year, as the surface water cools, it becomes heavier than the water beneath it and sinks to the bottom of the lake and the bottom water then rises to the top, resulting in a turning over of the water in the reservoir. This sometimes has an important bearing in the quality of water furnished to city water supply systems.

The water flowing into lakes is sometimes at a different temperature than that in the lake and density currents of the underflow, interflow, and overflow types are set up in the same way as the turbidity currents previously described. Such currents have been observed in the Swiss Lakes, (23) and are an important factor in making them suitable for bathing in the summertime.

Detailed observations were made by Bell, (25) where a complicated set of currents were produced by a stream of colder water entering the lake and mixing with the lake water. It was found that under favorable conditions a density current was possible when the specific gravity of the mixture varied as little as 0.01 percent from that of the lake water.

Mechanics of Density Currents

It will be readily seen that the velocity of flow of density currents will be increased for increasing values of the effective density of the flow, the thickness of the layer, and the slope of the reservoir bottom. O'Brien (2 p743) has shown that it is approximately proportional to the square root of the product of these quantities.

As the layer of turbid water passes under, over, or through the clear water, it may mix with the clear water or may remain entirely separate from it, with a sharp surface of separation between them known as an interface. Whether or not there is mixing at the interface can be established by the analysis used to determine whether or not waves at the surface of two fluids moving at different velocities, such as air and water, will break. The treatment developed by Lamb is given by Knapp (8). A great deal of work on this subject has been done by Keulegan at the U. S. National Hydraulic Laboratory (28, 29, 30, 32).

Those who wish to investigate this phase of the subject further are referred to the additional information supplied by Monish (2 p752), Einstein (17), O'Brien and Chernov (20), Craya (26 and 35), Farmer (32), Hamada (38), and Schijf and Schonfeld (39).

Miscellaneous Facts About Turbidity Currents

It is probable that turbidity currents are prominent in only a part of the reservoirs. Dobson (2 p759) examined the results of surveys of 55 reservoirs and in only two were there decided evidence of such currents, although others showed inconclusive evidence of them.

Brown (6 p68) has collected a great deal of information on the velocities and concentrations involved in turbidity currents. The velocities range from 3 to 0.1 feet per second. They have occurred on slopes as low as 1 foot per mile. The sediment concentrations ranged from 7.8 percent to as low as 0.007 percent and the depths of the currents from a few inches up to more than 100 feet.

The sediment carried by turbidity currents is very fine, and usually consists almost entirely of silt and clay sizes, ordinarily with the clay sizes predominating. The composition of the deposits on the bottom of Lake Mead is shown in Figure 4.

APPENDIX I

Data on Turbidity Currents in Reservoirs

Lake Mead Above Hoover Dam

The reservoir from which the most data are available regarding its density currents, is Lake Mead, which is located on the lower Colorado River in Nevada and Arizona. Extensive studies of the flows in this lake have been reported in detail (2, 9, 12c, 41).

Lake Mead has a maximum length of 120 miles and the original bottom slope of the river bed averaged about 4.6 feet per mile. During the early stages of filling of the reservoir, water was discharged through sluice gates at the bottom of the reservoir, and the turbidity currents were plainly evident in the turbid water discharged. When the lake had filled to the level of the powerhouse intake, about 260 feet above the stream bed, these temporary outlets were permanently blocked and since that time no turbid flow has passed out of the reservoir. Samples have been taken at frequent intervals in the reservoir just upstream from the dam, and although all small flows may not have been detected, it is believed that all large ones have been determined, since they cause a rise in the level of the interface between the turbid and clear water stored above the dam. Since this level settles very slowly after a turbid inflow, a large flow would be indicated, even though no measurements were taken while it was in progress.

Most of the following information on Lake Mead sediment is quoted from Gould's (12c) very complete report. The overflow type currents occur in the late spring and early summer. The water in the river has about the same temperature as that in the lake, but is much less saline; hence, the river water is less dense and flows on top of the lake water. The overflows seldom travel beyond the Virgin Basin, about 25 miles upstream from the dam, and none have reached the dam. Interflows occur in August and September, when the temperature of the inflowing water is about equal to that near the surface of the lake, but has a much higher salinity, which gives it a greater density than the surface water of the lake but not a greater density than the cold water near the bottom of the lake.

Underflows are the dominant and most important currents transporting sediment. In the late spring and summer, overflows and interflows are periodically replaced by underflows, but during the fall and winter there is a continuous movement of turbid water along the lake bottom. From October to April, Colorado River water is colder, more saline, and has more sediment than the deeper strata of water at the upstream part of the lake. All three of these cause the inflowing water to sink beneath the clear water and follow along the Colorado River channel. During this period, the division line between the turbid water and the clear lake water is sharp and

distinct, and commonly marked by an area of driftwood collected at the point of conveyance by opposing currents.

Most of the underflows do not reach the lower part of the lake. Records show that only 12 conspicuous underflows have traveled to the dam. Of these, 11 occurred in the first 7 years (1935-1941) when the lake was 70 to 120 mile long. The only other major flow to reach the dam was in the fall of 1947, when the lake was 78 miles long. In the first 14 years of operation, close to 2,000 million tons of sediment accumulated in the reservoir and occupied about 0.42 cubic miles or 5 percent of the reservoir capacity. Very close to half of the total weight and two-thirds of the total volume of this sediment have been transported by turbidity currents. Of this material, about 80 percent has accumulated on the reservoir floor at a distance of more than 43 miles from the original river entrance into the reservoir, and about 23 percent has accumulated at a distance of more than 100 miles. Because of the forward movement of the delta, the exact distance of travel of this material in turbidity currents cannot be determined. Most of the sediment that is deposited more than 100 miles from the original head of the delta traveled at least 70 miles. By 1948 the maximum depth in the reservoir based on the maximum water surface elevation was reduced from approximately 580 to 475 feet, and the mean depth based on the maximum water surface elevation was reduced from 209 to 200 feet. From 1948 to 1953 the depth of sediment in the reservoir near the dam has consolidated approximately 15 feet. The result of this consolidation of the sediment deposit has been an increase in depth of water at the dam of approximately 15 feet since 1948. The theory that as the submerged river channel fills with silt the underflows no longer stay within a channel but tend to spread out over the lake bottom and dissipate in the upper portion of the reservoir appears to apply at Lake Mead. No major underflows reaching the dam have been detected since 1947. If the underflows continue to dissipate before reaching the dam, the depth of the reservoir at the dam will not change materially for many years to come. A longitudinal section through the deposits in the channel at Lake Mead are shown in Figure 4. The depth of deposit along the channel is shown in Figure 3.

The material deposited at the upper end of Lake Mead is sand and coarse silt. That deposited on the bottom is composed of fine silt and clay. The material carried by the turbidity currents has an average median diameter of 1.65 microns in the dispersed state, and consists of 67 percent clay size, 32 percent silt, and less than 1 percent sand. The coarsest deposits are near the upper end and the finest near the lower end of the reservoir. Figure 4 shows the distribution and the sizes in the deposits.

The material in the turbidity currents was flocculated, the finer the material the greater the flocculation. The median diameters of the dispersed material decreased in a downstream direction from 5.0 to 0.9 microns, and the effective diameter of the flocculated particles from 13 to 11 microns.

The densities of the underflows in most cases reached peaks of 1.02 or greater, but in the first underflow it was only 1.012 and the May 1939 peak reached only 1.006. Some of the turbidity currents maintained a velocity of as high as 1 foot per second through practically the whole of the 115-mile length of the lake. Bell (4) estimated the velocity of the three underflows reaching the dam at approximately 0.83 foot per second. Similar records of the Bureau of Reclamation (9) show that the average velocities of the later currents were generally less than 0.5 foot per second and commonly as low as 0.3 foot per second. These records also indicate that the underflows travel much more rapidly over the steeper, upper parts of the delta than over the flatter, lower portions. Mean velocities of 1.0 foot per second are common at the mouth of the river where the turbid water plunges beneath the lake, but by the time these currents reach the Boulder Basin their velocities are less than 0.25 foot per second and are often too low for measurement. The depth of flow of the underflows is generally only a few feet. Above Iceberg Canyon, about 14 miles below the river entrance, the underflow is confined to the deepest part of the reservoir. In the November 1948 flow the depth of turbidity current in this section averaged 3 feet.

There is evidence from the distribution of sediment accumulated in Lake Mead that small underflows must take place along the steep slopes normal to the deep submerged channel of the Colorado River. If minor underflows of this type were not active in Lake Mead, the sediment that is dropped from the overflows would be expected to be found accumulated over a great part of the lake bottom. Investigations of the distribution of the accumulated sediment show that essentially all of the sediment brought into the lake by the Colorado River turbidity currents is confined to the region of the submerged Colorado River channel and no appreciable sediment from this source has accumulated in other areas of the lake bottom. It seems probable therefore, that the sediment dropped from the overflows in the shallow lake areas must continue to travel along the bottom until it reaches the deep submerged channel of the river.

Elephant Butte Reservoir

Elephant Butte Reservoir is located on the Rio Grande in New Mexico. It is about 40 miles long and originally had a storage capacity of 2,638,000 acre feet. The average stream slope of the reservoir bottom originally was 4.7 feet per mile. The Rio Grande carries a heavy load of sediment, averaging 1.18 percent concentration, which is probably the largest concentration of any river of equal discharge in the United States. A short distance upstream from the upper end of this reservoir, the Rio Grande is joined by the Rio Puerco, which possibly carries the highest concentrations of sediment in the world. Samples which contained sediment weighing up to 68 percent of the total sample weight having been obtained (11). It is probably flows from this stream which were responsible for most of the density currents observed in the Elephant Butte Reservoir. The composition of

the sediment flow from this stream is largely of clay size particles.

Data on all the flows recorded for Elephant Butte Reservoir, supplied by Mr. W. F. Resch, are given in Tables 1 and 2. The first of these tables gives dates of the density current inflow and the average and maximum tons of sediment per acre foot of water, and the second table gives the same data for the outflowing current. The weight per acre foot has been based on a unit weight of the mixture of sediment and water of 62.4 pounds per cubic foot. Weights observed in 1931 were 63.5 and 65.3 pounds per cubic foot, and in 1933 twelve measurements ranged from 62.39 to 63.75 pounds per cubic foot. The values given are therefore probably slightly too low.

In practically all cases concentrations of outflowing currents are less than for the inflowing currents. Observations showing the reverse to be the case are very likely due to the variation of the sediment flow not being accurately defined, sediment samples not being taken often enough, and/or the flashy nature of the inflow.

Only one density current flow in Elephant Butte Reservoir has occurred since 1935. In the first 20 years there were 13 flows, and in the second 20 years, only 1. This is probably due to a variety of causes, among them being the growth of vegetation in the upper end of the basin, and the shallow nature of the density flows, as previously mentioned.

Little data are available on the quantity of sediment carried by these currents. The outflow of July 1919 was estimated to carry 2,500 acre feet of sediment. Fiock (18) estimated that the total sediment outflow up to about 1933 was less than 4,000 acre feet, or only 2 or 3 percent of the total sediment inflow. Since that time the percent removed has been still less.

The following interesting information is also given by Mr. Resch: "It is interesting to note on Table 3 that the silt stratum was approximately 14 feet in depth a thousand feet above the dam. During August 8 and August 9 this run of silt was followed through the reservoir and at no place was the layer of silt found to be more than 2 feet in thickness until after it had reached the dam, whereupon a curling effect must have occurred that threw the silt back on itself and thus increased the thickness of the stratum. This phenomenon was not understood at that time; had it been, more detailed observations would have been made in the vicinity of the dam to more definitely define the point at which the silt stratum began to deepen as a result of the approach to the face of the dam or as a result of the probable curling effect after impinging against the face of the structure.

"I personally followed this silt flow through Elephant Butte; and during the observation for determination of the thickness of the silt stratum, I was amazed in finding that it never exceeded 2 feet in depth. This definition of the thickness during these observations occurred in a distance along the old river bed of the lake of some 16 to

Table 1

DENSITY CURRENTS FLOWING INTO ELEPHANT BUTTE RESERVOIR

<u>Date</u>	<u>Tons of sediment per acre-foot of water</u>	
	<u>Average</u>	<u>Maximum</u>
1917 A few days no data		
1919 July 5-22	88	146
July 31-Aug. 9	84	201
1921 July 23-29	119	153
August 1-4	71	95
1923 September No detailed data available		
1927 Sept. 9	139	139
Sept. 15	49	49
1929 Aug. 8-16	79	146
Aug. 25-Sept. 5	58	91
1931 Sept. 19-25	120	141
1933 June 15-28	58	124
1935 July 28	1.6	1.6
Aug. 5-6	84	96
Aug. 18-22	99	171
1941 May No data		

Table 2

DENSITY CURRENTS FLOWING OUT OF
ELEPHANT BUTTE RESERVOIR

<u>Date</u>	<u>Tons of sediment per acre-foot of water</u>	
	<u>Average</u>	<u>Maximum</u>
1917 A few days no data		
1919 July 7-10	51	51
July 15	51	51
July 18-28	87	126
1921 A few days no detailed data		
1923 Sept. 22-26	14	25
1927 Sept. 19-21	79	83
1929 Aug. 13-31	32	64
Sept. 26-Oct. 7	58	83
1931 Sept. 22-25	56	71
1933 June 23-30	43	67
1935 Aug. 9-11	28	50
Aug. 25-26	21	25
1941 May 9 A few hours no data		

Table 3

**TEMPERATURES, SALT AND SEDIMENT CONTENT,
ELEPHANT BUTTE RESERVOIR AUGUST 9, 1935**

Observations taken 1,000 feet above Dam.

Elevation in Lake	Depth of Water	Temperature Degrees F	Parts per million	
			Salt	Silt
4335.8	Surface	80	400	0
34.8	1	79		
30.8	5	78		
25.8	10	78		
15.8	20	77		
05.8	30	76		
4295.8	40	74		
85.8	50	71	540	60
75.8	60	69		
70.8	65	66		
65.8	70	65		
60.8	75	64	600	100
55.8	80	64	600	0
54.8	81	64	600	0
54.3	81.5	65		
53.8	82	68	700	1,100
52.8	83	69	900	11,000
50.8	85	71	900	30,800
45.8	90	72	1,100	41,800
40.8	95	72	1,000	37,000
39.8	96	71	1,100	45,300
4239.3	96.5 (Bottom)			

17 miles. Another peculiar condition that I noted during these observations was that the change from clear water to extremely silty water took place within 0.3 or 0.4 of a foot, the change being very abrupt between the clear and muddy water."

Lake Texoma, Oklahoma-Texas

Lake Texoma is on the Red River in the States of Texas and Oklahoma. The only turbidity current which has occurred in this lake since operation started in 1945 was during the flood of May 1951. At the time the flood started, the storage in the reservoir was 2,540,000 acre feet, and the length of the reservoir was 50 miles. About 4 days after the muddy inflow reached the upper end of the reservoir the turbidity current started to flow at the lower end of the reservoir and this flow lasted 3 days, at which time the storage had increased to 3,440,000 acre feet. The peak inflow was 146,000 cfs, which was the highest flow since 1908. The daily data on flow and sediment concentration during the flood are given in Table 4.

Grain-size analyses showed that of the sediment in the Red River inflow about 40 percent was finer than 0.004 mm, 40 percent between 0.004 and 0.062 mm, and 20 percent coarser than 0.062 mm. In the outflow it was found that about 54 percent was finer than 0.004 mm, 44 percent between 0.004 mm and 0.062 mm, and only about 2 percent coarser than 0.062 mm. It was estimated that not more than 15 percent of the inflowing sediment passed through the reservoir.

The Bureau of Reclamation is indebted to the United States Corps of Engineers for the data on this turbidity flow.

Table 4

DATA ON TURBIDITY CURRENTS IN LAKE TEXOMA

Date 1951	Red River inflow		Outflow from reservoir	
	Mean daily flow at Gainesville Gage on Red River (cfs)	Suspended sediment concentration (% by weight)	Mean daily flow at Colbert Gage (cfs)	Suspended sediment concentration (% by weight)
May 18	1,090		3,490	Clear
19	35,800	1.35	3,320	Clear
20	84,500	0.85	5,580	Clear
21	138,000	0.49	11,300	Clear
22	117,000		22,500	Clear
23	64,300	0.45	32,400	0.39
24	34,000	0.47	38,600	0.86
25	22,100		38,100	
26	14,900		39,600	Clear
27	11,800		37,100	Clear
28	11,100		38,600	Clear

Conchas Reservoir, New Mexico

The Conchas Reservoir (11) is located on the South Canadian River in New Mexico, just below its junction with the Conchas River, and the dam backs water up both streams. The slope in the Conchas arm is 12 feet per mile and in the South Canadian arm 8 feet per mile. The lengths of the two arms are about 12 and 23 miles respectively. Eighty percent of the sediment deposited in the reservoir was in the delta at the head of the reservoir and 20 percent on the reservoir bottom.

Between the closure in 1939 and the 1949 survey, from 6,000 to 15,000 acre feet of sediment are estimated to have passed through the outlet conduits as density currents. This represents from 15 to 30 percent of the total inflowing sediment. Between 1939 and 1944, 20 to 38 percent of the total inflowing sediment during this period had passed through the reservoir and outlets as density currents. This is the largest percentage of sediment passing through a reservoir by density currents of all reservoirs studied. The concentration of the sediment at the outlet works reached a high of 5.0 percent.

Turbidity Currents in Lake Issaqueena

Lake Issaqueena (14) is located in the Piedmont region of South Carolina. The streams of this region commonly carry sediment, more than 90 percent of which is composed of fine material. It had an original capacity of 1,836 acre feet and a length of 7,400 feet. The bottom slope was 24 feet per mile. The observed rate of filling was about 1.6 percent per year. Considerable data on turbidity currents in this lake were collected by the United States Soil Conservation Service.

Between August 1940 and April 1942 on nine occasions an increase of the concentration of the sediment in the water flowing out of the reservoir was observed with no increase in sediment concentration of the water at the surface of the lake. Each of these cases occurred after heavy rainfalls and a rise in stage of the inflowing stream, showing that density currents had occurred. In one case the inflowing water carried 1,071 parts per million of sediment and the outflowing water reached a concentration of 504 parts per million. On a number of occasions the muddy water was observed to form a deep layer at the bottom of the lake, which drained out slowly. On one occasion when the velocity of flow of the turbidity current was estimated, it was found to be not over 0.1 foot per second. Thick deposits were observed on the bottom of the lake near the dam, similar to those in Lake Mead. The data taken were not in sufficient detail to indicate quantitatively what reduction in reservoir deposits would be possible by controlling this reservoir to discharge as much sediment as possible through the outlets, but enough information was collected to indicate that this would not be a large part of the inflowing material.

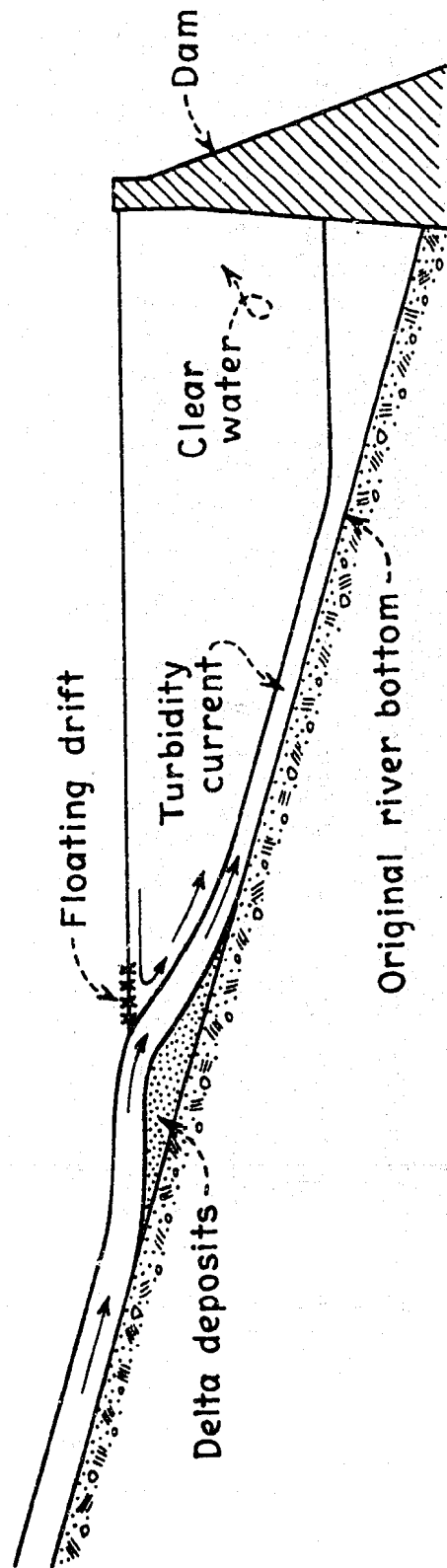


FIGURE I - UNDERFLOWING TURBIDITY CURRENT IN A RESERVOIR
PLUNGING TYPE

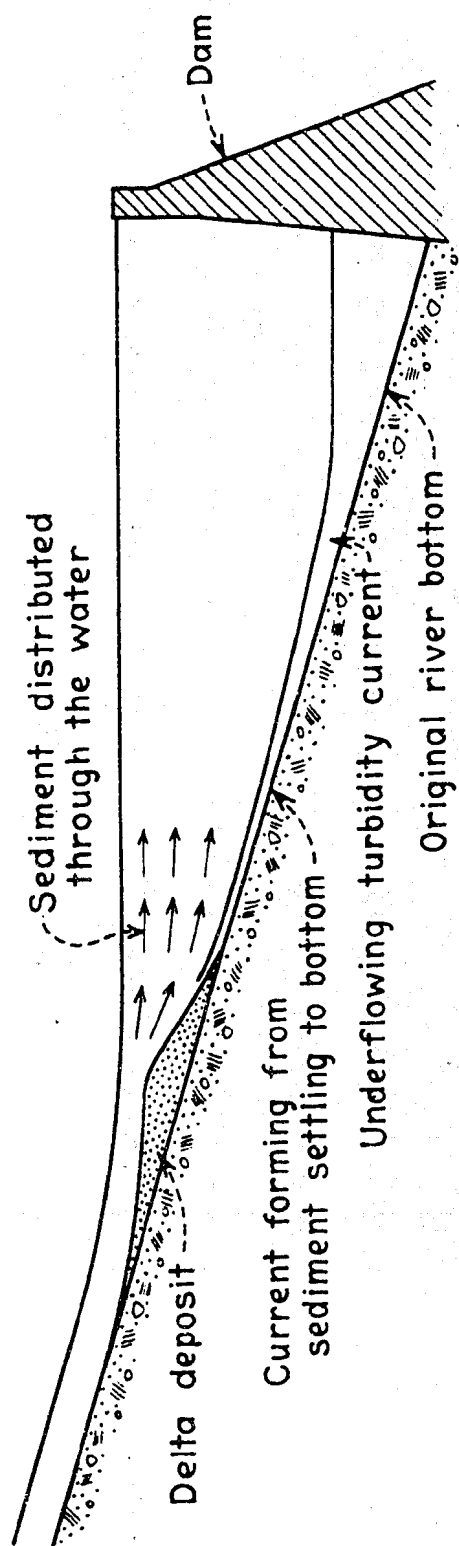


FIGURE 2 - UNDERFLOWING TURBIDITY CURRENT IN A RESERVOIR
SETTLING TYPE

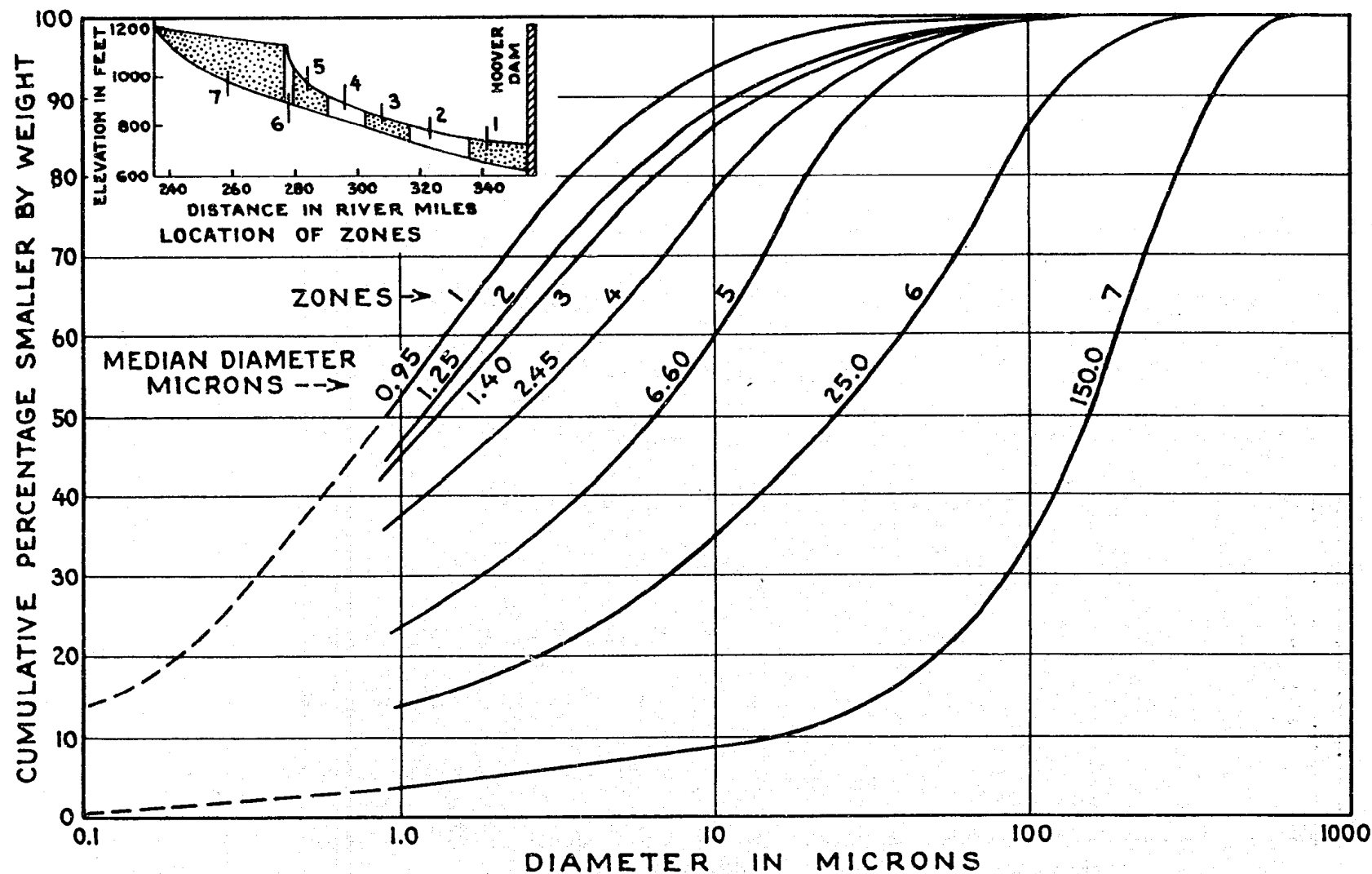


FIGURE 3 - CUMULATIVE CURVES SHOWING THE ESTIMATED MEAN SIZE COMPOSITIONS OF SEDIMENT IN LAKE MEAD ABOVE HOOVER DAM

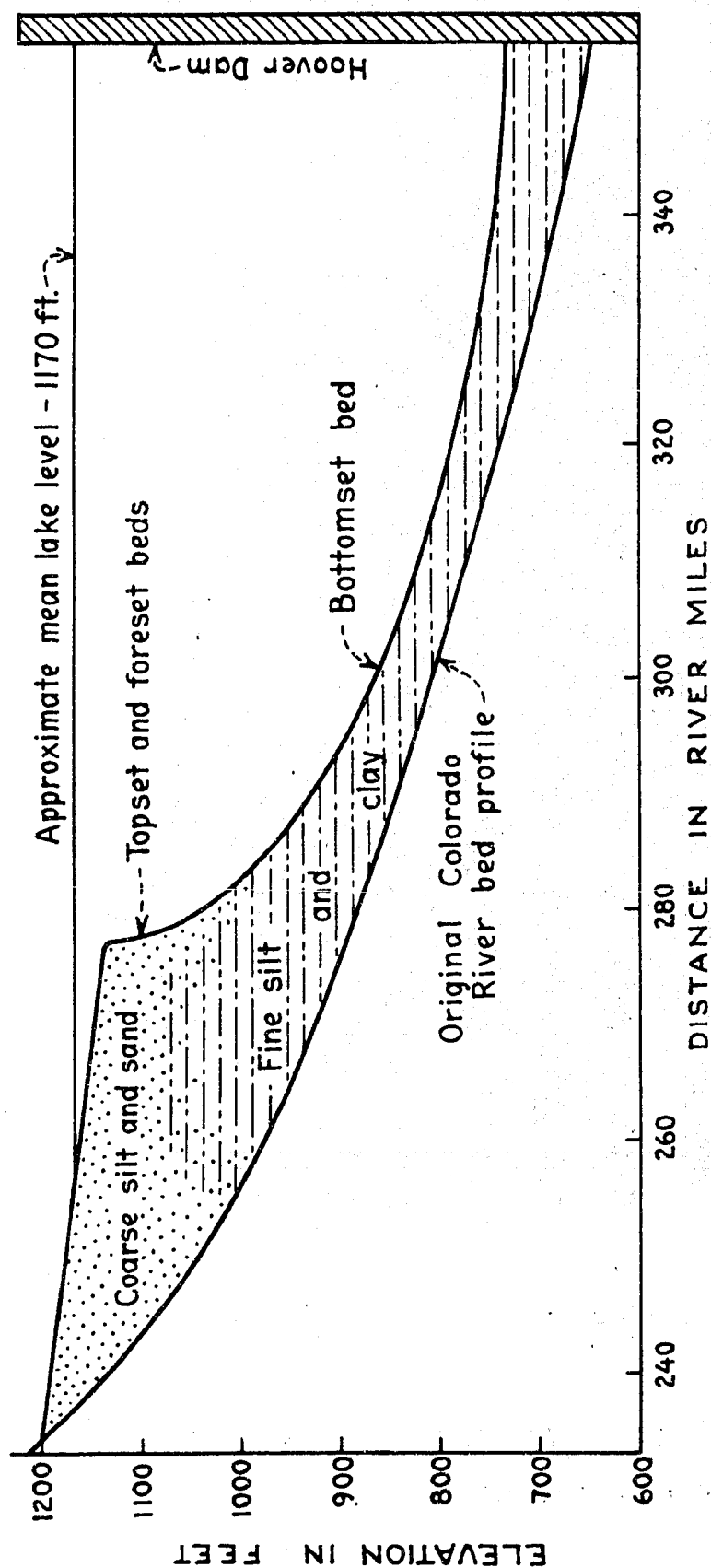


FIGURE 4 -- LONGITUDINAL SECTION THROUGH THE DEPOSITS
IN LAKE MEAD ABOVE HOOVER DAM

APPENDIX II

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